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PULSE-TECHNIQUE MEASUREMENT OF SOUND VELOCITY IN THE SEA.(U)

MAR 50 W H BURT

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STATEMENT OF PROBLEM

Bureau of Ships problem NEL 2A5a: "Develop equipment for continuous measurement of vertical sound velocity distribution for prediction of sonar performance, correction of vertical triangulation ranges, and target-depth measurements." This report deals with the development and testing of a Pulsed Sound Velocity Indicator (PSVI) for use on submarines and employing short-path high-frequency echo ranging for measurement of sound velocity.

CONCLUSIONS

1. The PSVI is suitable for direct measurement of underwater sound velocities from a submarine.
2. The accuracy of the measurements made with the PSVI is $\pm$ 1.2 feet per second, corresponding to an error of $\pm$ 0.025 per cent.
3. Changes in sound velocity as small as 0.2 foot per second can be detected and measured.
4. Previously used tables in which sound velocities are presented as a function of temperature, salinity, and depth show values as much as 5 feet per second less than those measured with the PSVI.
5. The following expression is proposed as the best representation of sound velocity as a function of temperature, salinity, and depth, for temperatures below 63 degrees F: $\underline{V} = 4241.59 + 13.147\,T - 0.06649\,T^2 + 4.27\underline{S} + 0.0182\underline{D}$, where $\underline{V}$ = velocity in feet per second, $\underline{T}$ = temperature in degrees F, $\underline{S}$ = salinity in parts per thousand, $\underline{D}$ = depth in feet.

RECOMMENDATIONS

1. Develop a recorder for use in conjunction with the PSVI.
2. Develop a computer to give density of sea water from velocity, temperature, and depth data, disregarding salinity.
3. Use the PSVI to make measurements of sound velocities over a wider range of water temperatures than here reported.
4. Use the PSVI to make measurements of sound velocity over a wider range of salinities than here reported.

WORK SUMMARY

A 100-kc and a 1-Mc model of the PSVI were constructed and tested. The latter proved satisfactorily accurate and was used in a series of sound-velocity measurements in sea waters ranging in temperature from 30 degrees F to 63 degrees F. The program was carried out by W.H. Burt and C.K. Lisle under the direction of R.M. Sherwood.

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INTRODUCTION

Within the framework of the Bureau of Ships assignment to develop equipment for continuous measurement of vertical sound velocity distribution, the Laboratory has undertaken the development and testing of a Pulsed Sound Velocity Indicator (PSVI) for use on submarines. The PSVI employs short-path high-frequency echo ranging for direct measurement of sound velocity.

Sound velocity measurements are of particular interest to those engaged in underwater sound research, since the vertical distribution of sound velocity determines the amount by which a sound beam is refracted. Vertical refraction of a horizontally directed sound beam is one of the chief factors influencing the range of underwater transmission. Thus a knowledge of the sound velocity distribution is essential to prediction of sonar ranges.

HISTORICAL BACKGROUND

The velocity of sound in a fluid is given by the expression

$$V = \sqrt{\frac{\gamma}{\rho\kappa}}$$

where

V = velocity of sound,

γ = ratio of specific heats of the fluid

ρ = density of the fluid, and

κ = true compressibility of the fluid.

When it is desired to use this expression for calculating the velocity of sound in the sea it is possible to relate γ, ρ, and κ to the given conditions of temperature, salinity, and depth by means of empirical formulas derived from field and laboratory measurements.

Several tables [4, 5, 10] (see list of references) giving sound velocity in terms of temperature, salinity, and depth have been published. Those of Kuwahara[5] appear to be the most rigorous and will be frequently referred to in the following text, although they differ only slightly from those of the British Admiralty.[4] The accuracy of these tables depends upon the accuracy of the empirical formulas used to relate the ratio of the specific heats, the density, and the compressibility to the given conditions of temperature,

salinity, and depth. Kuwahara uses values for the compressibility of sea water obtained from Ekman's[3] work in which the error is estimated by Ekman to be less than 0.3 per cent. An error of 0.3 per cent in κ, however, permits a deviation of $\pm$ 7.5 feet per second in the computed sound velocity.

These computed tables have formed the basis for most indirect determinations of sound velocity in the sea. A measurement of temperature, salinity, and depth is made, and the corresponding sound velocity is obtained from the tables. Any errors in the measurement of temperature, salinity and depth will, of course, be combined with the possible error of approximately $\pm$ 7.5 feet per second in the tables.

The extensive use of indirect determinations of sound velocity arises from the difficulties encountered in making direct measurements. The usual technique employed in earlier direct measurements [2, 4, 8, 9, 11] of sound velocity in the sea has required an explosive charge as a sound source and several hydrophones[11] spaced along an accurately measured base line as receivers. The arrival times of the pressure wave at successive hydrophones were compared, and these observations were used to compute the average velocity of sound over the base line. Care was taken to minimize the errors caused by refraction and reflection of the sound wave; by making measurements only at neap tides the effect of tidal flow was reduced. The chief objection to most of these previous measurements is that collateral observations of temperature and salinity were insufficient to describe water conditions along the entire sound path with the necessary accuracy.

Measurements made over a 12-mile base line by Woods, Browne and Cochrane,[11] offer more supporting data on temperature and salinity conditions than measurements made by others, but their methods are not adaptable for use in operational and tactical situations.

In contrast to the long distances used in previous direct measurements of sound velocity the Pulsed Sound Velocity Indicator uses a short path length. Refinements of time-measuring techniques make possible the accurate determination of sound velocity in terms of travel time along this short path. Water conditions in the sea are sufficiently uniform over the short distance used (approximately 26 ft) that a single temperature-salinity measurement may be used to represent conditions along the entire path. Thus it is possible to make accurate direct measurements of sound velocity with the PSVI, and to obtain conveniently temperature, salinity, and depth measurements with which to correlate these velocity readings.

DESIGN CONSIDERATIONS

The requirement to "develop equipment for continuous measurement of vertical sound velocity distribution for prediction of sonar performance, etc." demands also that the equipment be suitable for installation on Navy vessels. In view of the difficulties of indirect determinations of sound velocity — dependent on measurements of temperature, depth, and salinity, the latter by means of conductivity cells — a new approach to the problem was adopted: direct measurement of the travel time of a sound pulse over a short echo path.

In view of the requirements, it is obvious that velocities will be measured on a short sound path. Shortening the sound path requires refinement in time-measuring techniques.

An accuracy of $\pm$ 1.0 foot per second, or $\pm$ 0.02 per cent, was originally proposed as being appropriate. Taking 5000 feet per second as a convenient value for the velocity of sound in water, the allowable tolerances in the measurements of both time and distance are listed in table 1.

Table 1

Allowable Tolerances of Time or Distance

Path Length (feet)	Travel Time (microseconds)	Timing Tolerance (microseconds)	Distance Tolerance (feet)
200	40,000	8	.04
100	20,000	4	.02
50	10,000	2	.01 $\cong$ 1/8 in.
25	5,000	1	.005
12.5	2,500	0.5	.0025
6	1,200	0.24	.0012
3	600	0.12	.0006

On the basis of the figures in table 1, a path approximately 50 feet long was chosen as representing the best compromise between the requirements of accuracy and convenience.

The 50-foot path must be an echo-ranging path rather than a straight transmission path to eliminate the effect of the speed of the vessel on which the equipment is mounted. The actual distance for PSVI use was determined to be 52.056 feet — 26.028 feet from transducer to reflector, resulting in a travel time of approximately 10,500 microseconds for average velocity conditions.

The range of variation of sound velocity in natural waters is approximately 500 feet per second, resulting in a variation of about 1 part in 10 when 5000 feet per second is used as the nominal value. For convenience, the travel time over the 52-foot path may be considered as made up of two parts: the first part being a constant (10,000 microseconds) corresponding to a velocity of 5200 feet per second; the second part being a variable (0 to 1000 microseconds) corresponding to the drop of the measured velocity below this value. Then, if pulses of sound be emitted from the PSVI transducer at a repetition rate of 100 per second, a 10,000-microsecond interval will be provided between pulses — an interval which will serve to measure the "constant" portion of the travel time. The "variable" portion of the travel time, that which exceeds 10,000 microseconds, may then be measured on the calibrated sweep of an oscilloscope. Timing circuits will be required to initiate simultaneously the sound pulse and the oscilloscope sweep. Throughout the full range of transmission conditions, the echo of a given pulse will appear on the following oscilloscope sweep, and will be displaced along the sweep by a distance related to the amount by which sound velocity falls short of 5200 feet per second.

PSVI, MODEL X2

The Pulsed Sound Velocity Indicator, Model X2, is an experimental equipment designed for installation on a submarine. It is capable of direct measurement of sound velocity in the water through which the submarine passes while submerged. A quartz-crystal transducer mounted on the deck of the submarine sends 15-microsecond pulses of 1-Mc sound to a reflector mounted approximately 26 feet away. (PSVI, Model X1, built in 1948, operated at the lower frequency of 100 kc — see Appendix.) Timing circuits and the calibrated sweep of an oscilloscope afford accurate measurement of the travel time of the sound pulse to the reflector and back. A block diagram of the equipment is shown in figure 1.

PHYSICAL DESCRIPTION

The PSVI comprises two table-height racks, with the oscilloscope mounted above for convenient viewing (fig. 2). The two racks incorporate a Hewlett Packard Model 100C frequency standard; a driver, a receiver, and timing and trigger circuits. The oscilloscope used in the PSVI is a Dumont, Type 256-B, A/R Range Scope[1]. Originally designed for use with conventional radar sets to increase accuracy of range readings, this scope is calibrated in yards

(postwar models of this same scope are calibrated in microseconds).

Positions of the transducer and reflector on the deck of the submarine are shown in figure 3. To hold the error within $\pm$ 0.02 per cent, it is necessary that the distance between the transducer and reflector be established with an accuracy of $\pm$ 1/16 inch.

Assuming that the axis of the radiated sound beam is perpendicular to the reflector and is directed at its center, the path length of the sound pulse is here taken as twice the distance from the surface of the crystal to the center of the reflector. The rho-C rubber window covering the crystal is 0.1-inch thick. Taking this into account, a steel tape, accurate to 1 part in 10,000, is used to measure the distance between the outer surface of the rubber window and the center of the reflector. The half-path length is established at 26.028 feet; path length is 52.056 feet.

CIRCUITRY

Timing Circuits.

The timing circuits are the most important part of the PSVI. Their function is to provide a repetition rate of 100 pulses per second, constant to 1 part in 10,000, or better. As previously mentioned, the greater portion of the travel time of the sound pulse is measured by this constant time interval between pulses.

Figure 4 is a block diagram of the timing circuits. A crystal-controlled frequency standard, Hewlett Packard Model 100C, supplies outputs of 100 kc, 1 kc, and 100 cps, accurate to 1 part in 100,000. A triangular pulse derived from the 100-kc output is mixed with a pedestal pulse derived from the 1-kc output, and the result is a triangular pulse occurring 1000 times a second. This pulse is again mixed with a pedestal pulse originating from the 100-cycle output to produce a pulse occurring 100 times a second. In the final stage this pulse triggers a thyratron tube, the output pulse of which has an estimated rise time of 0.02 microseconds. This thyratron pulse, which has a repetition rate of 100 per second, triggers the driver and the oscilloscope sweep. A circuit diagram of the timing circuits is shown in figure 5.

Driver.

The driver circuits of the PSVI are a modification of those used in an early ultrasonic radar trainer[7]. A circuit diagram is shown in figure 6. V_1 is a multivibrator, V_2 acts as a switch tube, V_3 is a Hartley oscillator, and V_4, V_5, and

V_6 act in parallel as the driver amplifier. When the multivibrator, V_1, is triggered by the output pulse of the timing circuit, it generates a negative square pulse which is applied to the grid of V_2. By adjusting R_6, the width of the multivibrator output pulse can be varied. For normal operation a pulse width of about 2 microseconds is used. V_2 in its normal state is conducting, but it is driven to cutoff by the multivibrator negative pulse. Also connected to V_2 is the tuned circuit L_1C_9 of the Hartley oscillator. As long as the switch tube V_2 is conducting, L_1C_9 is prevented from oscillating. However, when V_2 is cut off, V_3 oscillates, and the oscillations are fed to the grids of the driver amplifier V_4, V_5, and V_6. The driver amplifier is biased to cutoff, so that the crystal is not driven until a trigger pulse initiates the sequence just described. A line transformer, L_2L_3, matches the output of the driver amplifier to the 55 feet of MCOS-2 cable used to connect it to the transducer. The grids of the driver amplifier are driven for only one or two cycles, but the resonant output circuit rings for approximately 15 microseconds because of the high _Q_ of the quartz-crystal transducer. Maximum rms amplitude of the 15-microsecond pulse is approximately 250 volts; about 6 cycles (out of the 15-cycle duration) are required for building up to this maximum amplitude.

Transducer.

An X-cut quartz crystal 1 inch square and resonant at 1 Mc is used as sound source and receiving hydrophone. It is mounted by cycle-welding to a rubber diaphragm which serves as the window of the transducer. The crystal is backed by a layer of Corprene 1/16-inch thick and a brass backing plate. A line-matching transformer, similar to L_2L_3 of figure 5, and a capacitor are mounted behind the backing plate; the remaining space is filled with castor oil. In the original design of the transducer a retaining ring was provided which would have held the crystal firmly against the backing plate. Because of assembly difficulties this retaining ring was omitted, introducing some uncertainty as to the exact position of the crystal. A small pressure against the rubber window is sufficient to push the crystal firmly against the backing plate, and it is believed that this occurred during dives, when, of course, no observations of the crystal were possible. Before further measurements are made with the PSVI equipment it is planned to modify the transducer so that uncertainty regarding the position of the crystal will be eliminated.

The reflector is a steel plate, 1/2 by 12 by 14 inches, welded to a vertical I-beam and bolted to the deck. During installation, care was taken to align the axis of the transducer perpendicular to the reflector. A plane

mirror and sighting device facilitated close alignment.

Receiver.

The receiver diagrammed in figure 7 is a three-stage amplifier tuned to a frequency of 1 Mc. When one transducer is used as both transmitter and receiver, the high-voltage driver pulse and the weak echo signal are both applied directly to the receiver input. Circuits are incorporated in the amplifier to attenuate the driver pulse and to amplify the relatively weak echo signal. Of the several limiter circuits tried, the simplest and most satisfactory for this application proved to be a diode limiter using crystal rectifiers. In the first two stages, type 1N34 rectifiers are used back-to-back to provide a low-impedance shunt for the high-voltage driver pulse, while offering a high impedance to the low-voltage echo signal. The first pair of crystal rectifiers is biased with 1.5 volts to reduce attenuation of the weak echo signal by conduction. Considerable limiting action also takes place in the second and third stages.

Amplifier response is shown in figure 8. For low-voltage inputs the amplifier is linear and has a gain of 66 db. For higher-voltage inputs, however, the cutoff becomes quite sharp so that for a driver pulse of 250 volts (rms) the gain is -14 db. Thus a total discrimination of 80 db is achieved in the amplification of driver pulse and echo signal.

In spite of the fact that all three amplifier stages are slightly detuned to increase the bandwidth, the pulse shape is nevertheless distorted to a considerable degree. Distortion is not a serious disadvantage in this application, however, since it is desired only to measure to arrival time of the first cycle of the echo pulse.

Oscilloscope.

As previously mentioned, the calibrated sweep on a cathode-ray oscilloscope is used to measure that portion of the travel time of the sound pulse which exceeds the repetition-rate interval of 0.01 second. In the PSVI a Dumont Type 256-B A/R Range Scope[1] is employed. This scope was designed for use with conventional radar sets for accurate reading of ranges, and is calibrated in yards. The range scales available on the scope are 200,000 yards, 4000 yards, and 2000 yards; corresponding to time bases for the oscilloscope sweep of 1220, 24, and 12 microseconds. The conversion factor is 163.9 yards equals 1 microsecond. The scope is so constructed that any 24-or 12-microsecond portion of the 1220-microsecond sweep can be selected by the operator and expanded to fill the scope screen for

critical measurement. Figure 9 is a photograph of the 1220-microsecond sweep, showing the outgoing pulse at the start of the sweep and the echo (of the preceding pulse) at the center of the trace. In figure 10 the first 24-microsecond portion of the same echo is expanded to fill the scope screen. Correct positioning for time measurement is shown, with the first cycle of the echo set at the start of the expanded sweep. Readings are made on the range dial which moves with the positioning of the expanded sweep. Readings are normally made to the nearest 100 yards of range, and converted to time by using 163.9 yards equals 1 microsecond.

The oscilloscope sweep and range dial are linear to within ± 0.1 per cent.

Current models of this Dumont Oscilloscope (designated Type 256-D) are calibrated in microseconds, rather than in yards, but the A/R scope described above was available at NEL and was deemed satisfactory for inclusion in experimental equipment.

FUNCTIONAL DESCRIPTION

Keying of the driver for transmission of the sound pulse also initiates the oscilloscope sweep. The keyed pulse appears at the beginning of the 1220-microsecond sweep and the echo of the preceding pulse (which was emitted 10,000 microseconds earlier) appears later in the trace. The displacement of the echo from the beginning of the sweep permits measurement of the time in excess of 10,000 microseconds required for the travel of the sound pulse along the measured echo path.

The echo trace is expanded (4000-yd or 24-microsecond scale) and positioned so that the first cycle of the echo is aligned with the beginning of the scope trace. The expansion of the echo trace permits accurate determination of the first cycle of the echo and facilitates positioning. Positioning of the first cycle of the echo gives a reading in yards on the range dial. A table, prepared for use with the equipment in this application, affords quick conversion of range reading directly into sound velocity.

MEASUREMENTS OF SOUND VELOCITY

SCOPE OF MEASUREMENTS

After preliminary testing of the PSVI, it was decided to make a series of sound velocity measurements with this equipment in order to determine experimentally the relation between sound velocity and the temperature, salinity, and

depth. Accordingly, measurements were made during May and August 1949, in widely different areas and water conditions (see table 2).

The first group of measurements was made during extended dives on 3 and 13 May 1949 in waters near San Diego. 110 separate observations were made while the submarine was operating at different depths and speeds. Water temperatures ranged from 50 to 60 degrees F.

Another series of sound velocity measurements was made in northern waters in August, during short dives at temperatures of 30 to 45 degrees F. During this series the submarine was kept stationary on the bottom whenever possible, which allowed more accurate determination of the temperature associated with a particular sound velocity measurement.

Table 2

Scope of Measurements - Concomitant Conditions

Date	Location	Depth (feet)	Temperature (°F)	Salinity (°/oo)	Number of readings in "set" of observations
3 May 49	San Diego	40 to 180	50.4 to 60.2	33.58 to 33.75	70 } 110
13 May 49	San Diego	60 to 180	50.9 to 58.3	33.58 to 33.75	40 }
5 Aug. 49	Northern Waters	138	32.6	32.6	5
5 "	"	105(B)	41.7	31.8	7
6 "	"	122(B)	40.4	32.07	6
6 "	"	92(B)	33.4	32.43	5
9 "	"	147(B)	30.2	32.29	7
18 "	"	125(B)	37.5	32.25	7
18 "	"	104(B)	44.4	30.52	5
18 "	"	113(B)	42.0	31.69	4
19 "	"	124	30.3	32.32	5
26 "	"	121	34.3	32.07	4
27 "	"	140	39.3	32.42	5

(B) indicates submarine was bottomed.

SUPPORTING MEASUREMENTS OF TEMPERATURE, SALINITY, AND DEPTH

It will be noted that, in addition to the velocity readings, table 2 contains values for temperature, salinity, and depth. A temperature-sensitive element and a conductivity cell were mounted on the deck of the submarine near the PSVI

transducer. Direct readings of temperature and specific conductance were obtained from equipment connected to these topside elements. Salinity was then computed from the values of temperature and specific conductance.

Independent determinations of temperature and salinity were also made on samples of sea water drawn directly through the submarine hull at a depth 10 feet greater than that of the PSVI transducer. Salinities were determined by titration of these samples. The accuracy of temperature measurements was kept high by flowing a considerable amount of water from the valve before sampling, and placing the sample and thermometer in a vacuum bottle. Normally the temperature and salinity values used were those obtained from the samples, while those obtained electrically were used as a check. When a difference in temperature was noted between water at the depth of the transducer and at the depth of the valve the data were discarded as unreliable.

Depths were read from the submarine's gauges.

The estimated accuracy of a single observation is as follows: temperature ± 0.15 degrees F, salinity ± 0.02 part per thousand, and depth ± 2 feet.

GENERAL PROCEDURE

Sound velocity measurements were made either with the submarine holding as constant a depth as possible at a speed of two knots, or with the submarine lying stationary on the bottom. The latter procedure was possible, of course, only in shallow water, but was preferable because of the smaller variations in water conditions encountered.

At a convenient time a water sample was drawn and readings were made simultaneously of the PSVI and the temperature and specific conductance meters. This procedure was repeated at intervals of about two minutes until four or more temperature measurements taken at a particular depth, over a period of fifteen to thirty minutes, were found to be consistent within ± 0.1 degrees F. The data were then considered reliable. Four or more consistent temperature observations, together with corresponding velocity determinations, are called a "set." In further treatment of the data each set was averaged to obtain a single value of sound velocity to correspond to a particular temperature-salinity-depth condition as shown in table 2.

TREATMENT OF DATA

Northern Data.

It will be noted from table 2 that the measurements of sound velocity were made over a rather wide temperature range, but over only a small range of salinity and depth. Since the effects of salinity and depth on sound velocity are small in comparison to the effect of temperature, it is not feasible to determine the relation of sound velocity to salinity and depth from these meager data. In order to depict sound velocity purely as a function of temperature, it is necessary to correct all velocity data to uniform conditions of salinity and depth. A salinity of 32.5 parts per thousand and a depth of 125 feet were chosen as best approximating the actual conditions of measurement. The following relations, given by Kuwahara[5], were used to make the corrections:

$$\Delta V_S = 4.27\ \Delta S, \text{ and}$$

$$\Delta V_D = 0.0182\ \Delta D,$$

where ΔV_S and ΔV_D are the sound velocity corrections in feet per second, ΔS the difference between the measured salinity and 32.5 in parts per thousand, and ΔD the difference between the measured depth and 125 feet.

A further correction was made to compensate for the change in length of the measurement path caused by thermal contraction and expansion of the hull of the submarine. This correction was applied on the following basis:

1. The best measurement of distance was made at a temperature of approximately 68 degrees F.
2. The coefficient of linear expansion of the submarine hull was taken as that of steel: 5.5×10^{-6} per degree F.
3. It was assumed that the hull took the temperature of the surrounding water during a dive.

The maximum sound velocity correction, corresponding to a water temperature of 30 degrees F, was -1.3 feet per second.

Values of temperature and sound velocity were then obtained for each dive in northern waters, by averaging the corrected results of each set of observations (see table 3).

San Diego Data.

The data of 3 and 13 May 1949 — when extended dives were made at varying temperatures, salinities, and depths — were treated somewhat differently. Not only were the 110 values corrected to a single salinity and depth, but they were also corrected to a mean temperature of 51.7 degrees F, using a velocity-temperature relation* based on Kuwahara's tables of sound velocity. The standard deviation of these 110 adjusted values was approximately 1 foot per second; an average velocity of 4885.1 feet per second was used to represent the set of observations. Because of the large number of observations in this set, it obviously merits more consideration than the other sets, and a weight of 5 has been assigned to it, relative to a weight of 1 for each of the other sets of observations.

Table 3. Values of Sound Velocity

(Velocities adjusted to $\underline{S} = 32.5$ ‰, and $\underline{D} = 125$ ft)

Temperature (degrees F)	Sound Velocity (fps)	Statistical Weighting	Source of Data
30.2	4720.6	1	PSVI
30.3	4720.6	1	PSVI
32.6	4738.1	1	PSVI
33.4	4748.6	1	PSVI
34.3	4754.4	1	PSVI
37.5	4782.4	1	PSVI
39.3	4795.7	1	PSVI
40.4	4805.1	1	PSVI
41.7	4812.4	1	PSVI
42.0	4818.1	1	PSVI
42.8	4825.4	1	Woods, Browne, Cochrane[11]
44.4	4836.4	1	PSVI
44.6	4836.0	1	Woods, Browne, Cochrane
51.7	4885.1	5	PSVI, San Diego Area
59.0	4925.1	1	Marti[6]
62.5	4944.9	1	Woods, Browne, Cochrane

*Since in most of the 110 observations the temperature was within ± 2.0 degrees of 51.7 degrees F, the correction was usually less than 15 feet per second. Secondly it may be seen in figure 11 that the curve representing Kuwahara's values and the least-squares fit of the experimental data are nearly parallel near 51.7 degrees F.

Table 3 lists the adjusted average velocities and the corresponding temperatures. Also included in the table are three values determined by Woods, Browne, and Cochrane,[11] and one value determined by Marti.[8] These are included principally to extend the range of experimental data available, and each value is given a weight of 1. It should be noted that these four values of sound velocity are the only previous measurements for which reasonably complete data on temperature and salinity are available.

RESULTS OF MEASUREMENTS

In order to obtain sound velocity as a function of temperature, a least-squares curve of the form $\underline{V} = \underline{A} + \underline{BT} + \underline{CT}^2$ was fitted to the data of table 3. The resulting equation is $\underline{V} = 4382.65 + 13.147\ \underline{T} - 0.06649\ \underline{T}^2$, where $\underline{V}$ is the velocity in feet per second and $\underline{T}$ is the temperature in degrees Fahrenheit. This equation applies to a salinity value of 32.5 parts per thousand, to a depth of 125 feet, and to temperatures below 63 degrees F.

In figure 11 the experimental data are plotted as a function of temperature, and the above equation is shown as a solid curve. It will be noted that the measured values lie quite close to this curve. The consistency of the data is shown by the standard deviation between the measured velocity values and the velocity values computed from the equation representing the least-squares fit of the data. This standard deviation is only 1.21 feet per second.

The dotted curve in figure 11 represents values obtained from Kuwahara's tables of sound velocity. It may be seen that the measured values of sound velocity exceed the computed values by a maximum of approximately 5 feet per second.

In view of the consistency and accuracy of the experimental measurements, and the possible inaccuracies of computed values of sound velocity, the above equation appears to be a better representation of sound velocity as a function of temperature than can be derived from computed tables.

Using previously noted expressions given by Kuwahara[5] relating sound velocity to salinity and depth, a more generally useful equation is obtained. This expression is $\underline{V} = 4241.59 + 13.147\ \underline{T} - 0.06649\ \underline{T}^2 + 4.27\ \underline{S} + 0.0182\underline{D}$, where $\underline{S}$ is the salinity in parts per thousand, and $\underline{D}$ is the depth in feet. Again this equation is limited to temperatures below 63 degrees F. It is believed that this more accurately represents sound velocity in the sea than expressions obtained from present tables of sound velocity.

DISCUSSION OF ERRORS

In the following discussion the values cited are not to be considered as precise, but rather as the best estimates of the errors. Errors in determination of sound velocity with the PSVI arise from errors in measurement of both time and distance.

Errors in the time measurement arise principally from uncertainty in recognizing the first cycle of the echo pulse, and from nonlinearity of the oscilloscope sweep. Accuracy of the repetition rate is one part in 100,000, so that the error of 0.1 microsecond from this source may be neglected. It seems certain that the start of the echo pulse can be recognized to within 1 cycle or ± 1 microsecond. The error caused by nonlinearity of the oscilloscope sweep is a systematic error and could be corrected by refinement of the measuring technique. However, since this nonlinearity may cause an error of ± 1 microsecond, depending upon the particular value of sound velocity, it is treated as a random error. The combined effect of these two errors makes the probable error in the determination of a single time interval ± 1.4 microseconds.

The error in the measurement of the path length is estimated to be ± 0.005 foot (approximately 1/16 inch). However, because of the mounting of the crystal (discussed previously), some uncertainty exists as to the exact position of the crystal under different pressure and temperature conditions. The possible movement of the crystal is estimated to be ± 1/16 inch, which may change the path length by ± 1/8 inch or ± 0.01 foot. The probable error then in the path length determination is $\pm\sqrt{(.005)^2 + (.01)^2}$ or ± 0.011 foot.

Using the above figures for the probable errors of time and distance measurements, the probable error of the velocity measurements made with the PSVI is ± 1.2 feet per second.

Temperature measurements on samples of water drawn through the hull of the submarine could nearly always be repeated by different observers to within ± 0.1 degree F. A more difficult error to estimate is caused by the difference in water temperature between the point at which the sample was drawn and that of the PSVI transducer. Because of the small temperature gradients in the operating areas this difference probably seldom exceeded 0.1 degree F. The probable error of the temperature determinations is estimated on this basis to be ± 0.15 degree F, approximately equivalent to 1.2 feet per second of sound velocity.

Normally, the error in salinity as determined by titration is ± 0.02 part per thousand, which is small. However, for two of the sets of observations included in the data no samples were obtained for titration, and the salinity was obtained from conductivity measurements. These measurements are accurate to ± 0.3 part per thousand, and thus the

resulting probable error of the salinity measurements is $\pm$ 0.24 part per thousand. This is equivalent to a velocity error of 1.0 foot per second.

Errors in depth measurements were normally less than 2 feet, and their effect on sound velocity is quite small: 0.04 foot per second.

The probable error then in sound velocity determined indirectly from measurements of temperature, salinity, and depth equals $\pm \sqrt{(1.2)^2 + (1.0)^2 + (.04)^2}$, or $\pm$ 1.6 feet per second.

Thus it is seen that the direct measurement of sound velocity with the PSVI, and the separate measurements of those factors influencing the sound velocity were made with approximately the same degree of accuracy; further, that the errors are rather small, being $\pm$ 0.025 per cent for the direct measurements and $\pm$ 0.032 per cent for the indirect determinations.

CONCLUSIONS

VELOCITY MEASUREMENTS

1. On the basis of direct measurements, sound velocity in the sea can be represented as a function of temperature by the following expression:

$$\underline{V} = 4382.65 + 13.147\underline{T} - 0.06649\underline{T}^2,$$

when the salinity is 32.5 parts per thousand, the depth is 125 feet, and the temperature is below 63 degrees F.

2. By combining the above expression with computed relations giving sound velocity as a function of salinity and depth, the following equation is obtained:

$$\underline{V} = 4241.59 + 13.147\underline{T} - 0.06649\underline{T}^2 + 4.27\underline{S} + 0.0182\underline{D}.$$

The last equation above, which applies below 63 degrees F, is believed to be the best representation currently available for sound velocity in the sea as a function of temperature, salinity, and depth.

3. Values of sound velocity given by the equation in 2 above exceed those obtained from Kuwahara's tables of sound velocity by as much as 5 feet per second.

THE PSVI

1. The present equipment is capable of direct measurement of sound velocity in the sea to an accuracy of $\pm$ 1.2 feet per second, or 0.025 per cent error. Proposed modification of the crystal mounting should reduce the error to $\pm$ 0.7 foot per second.

2. Changes in sound velocity as small as 0.2 foot per second can be detected and measured with the present equipment.

3. Chief disadvantage of the present equipment is the fact that an operator is required, and that readings cannot be obtained with sufficient speed during rapid changes of sound velocity.

RECOMMENDATIONS

1. It is recommended that the feasibility of developing a recording system for the PSVI be investigated. Such a development would plot sound velocity profiles with considerably greater accuracy than that obtained with present equipments.

2. It is further recommended that consideration be given the development of a computer to give density of sea water from velocity, temperature, and depth components but without salinity elements. No trouble-free device for continuous measurement of salinity is in sight. Here is a reasonable way to by-pass the difficulty. Development of such a computer naturally depends on successful implementation of the first recommendation.

3. It is recommended that the PSVI be used to measure sound velocity in sea water of temperature above 63 degrees F. Determinations in water of 70 to 80 degrees F would extend the present data to cover the complete oceanic sound-velocity range. These additional data could be readily obtained by installing the PSVI on a submarine making an equatorial cruise.

4. It is recommended that the PSVI be used to measure the effect of salinity on the velocity of sound. Since large salinity changes in the sea are not common, this effect can best be studied in the laboratory.

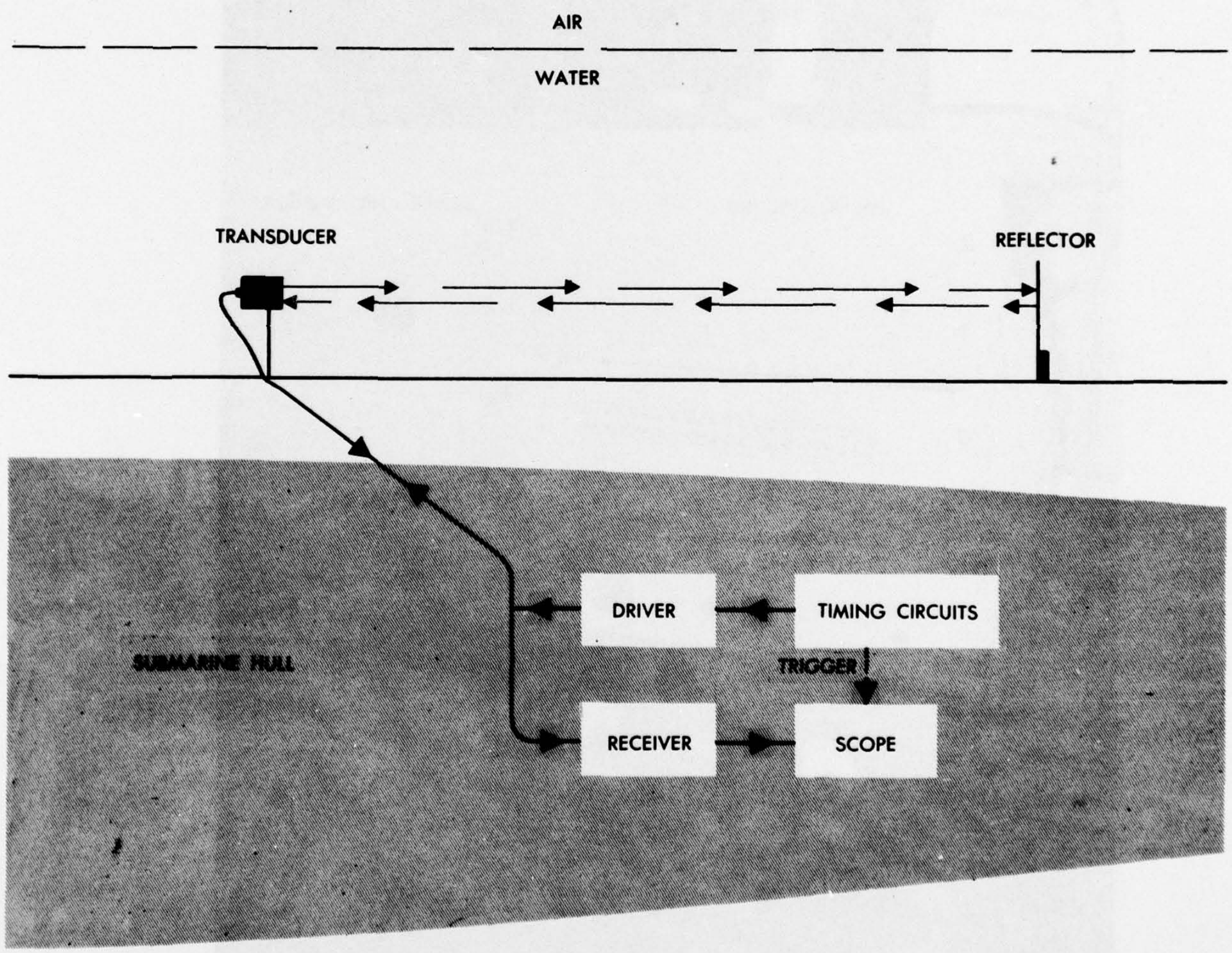

Figure 1. Block diagram of the pulsed sound velocity indicator.

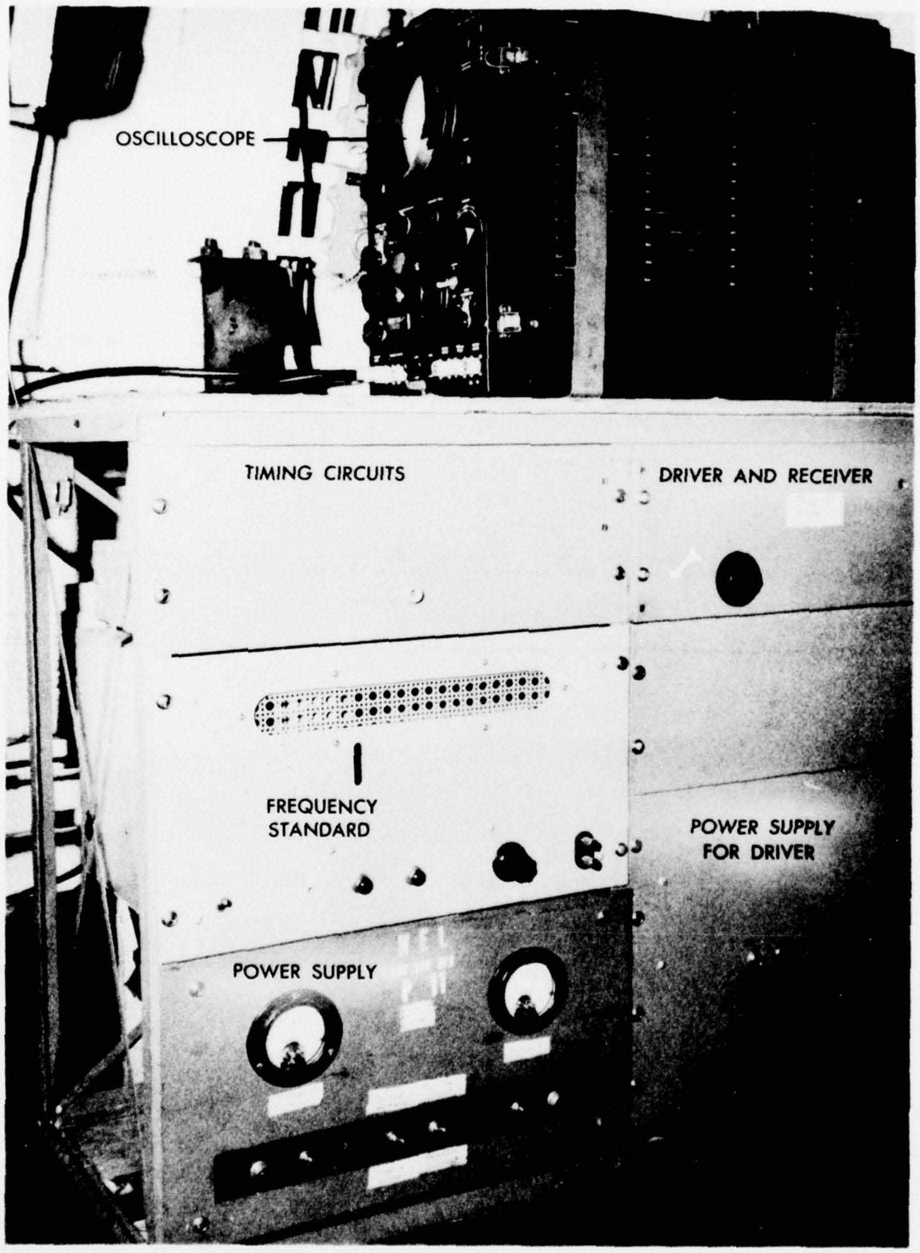

Figure 2. Interior submarine installation.

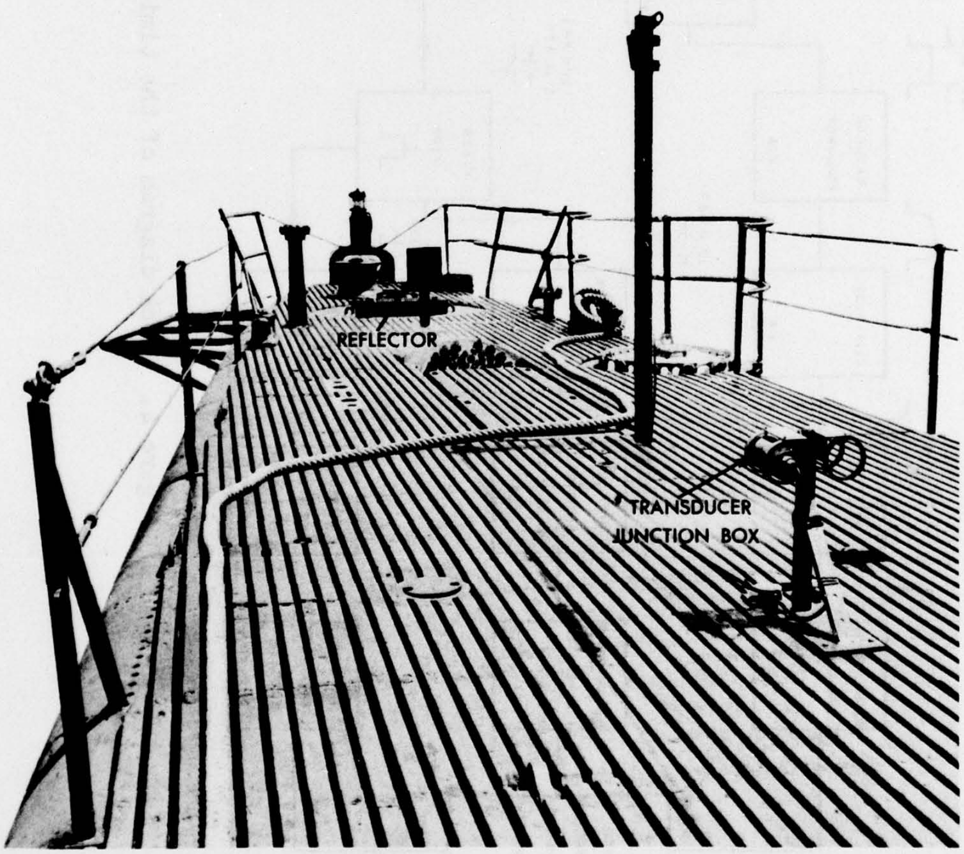

Figure 3. Exterior mounting of transducer and reflector.

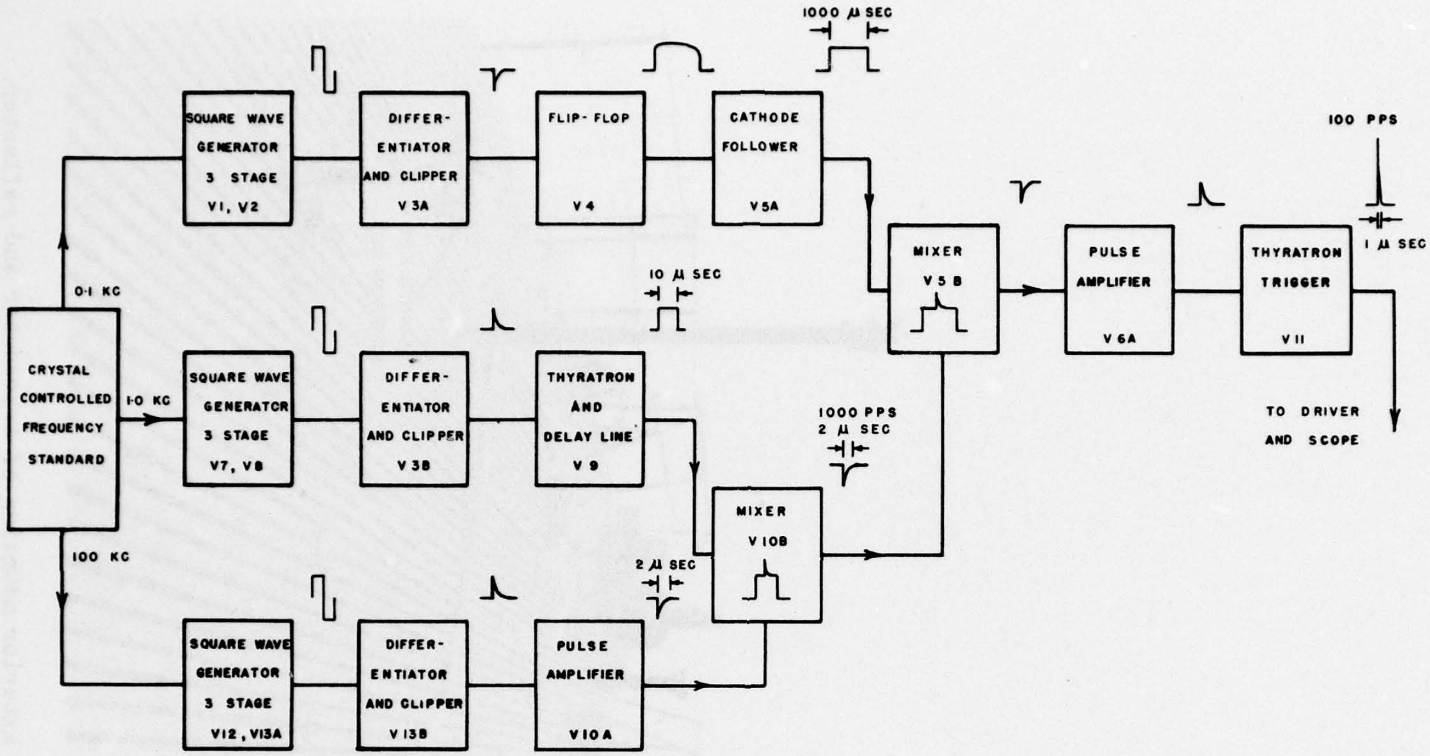

Figure 4. Block diagram of the timing circuits.

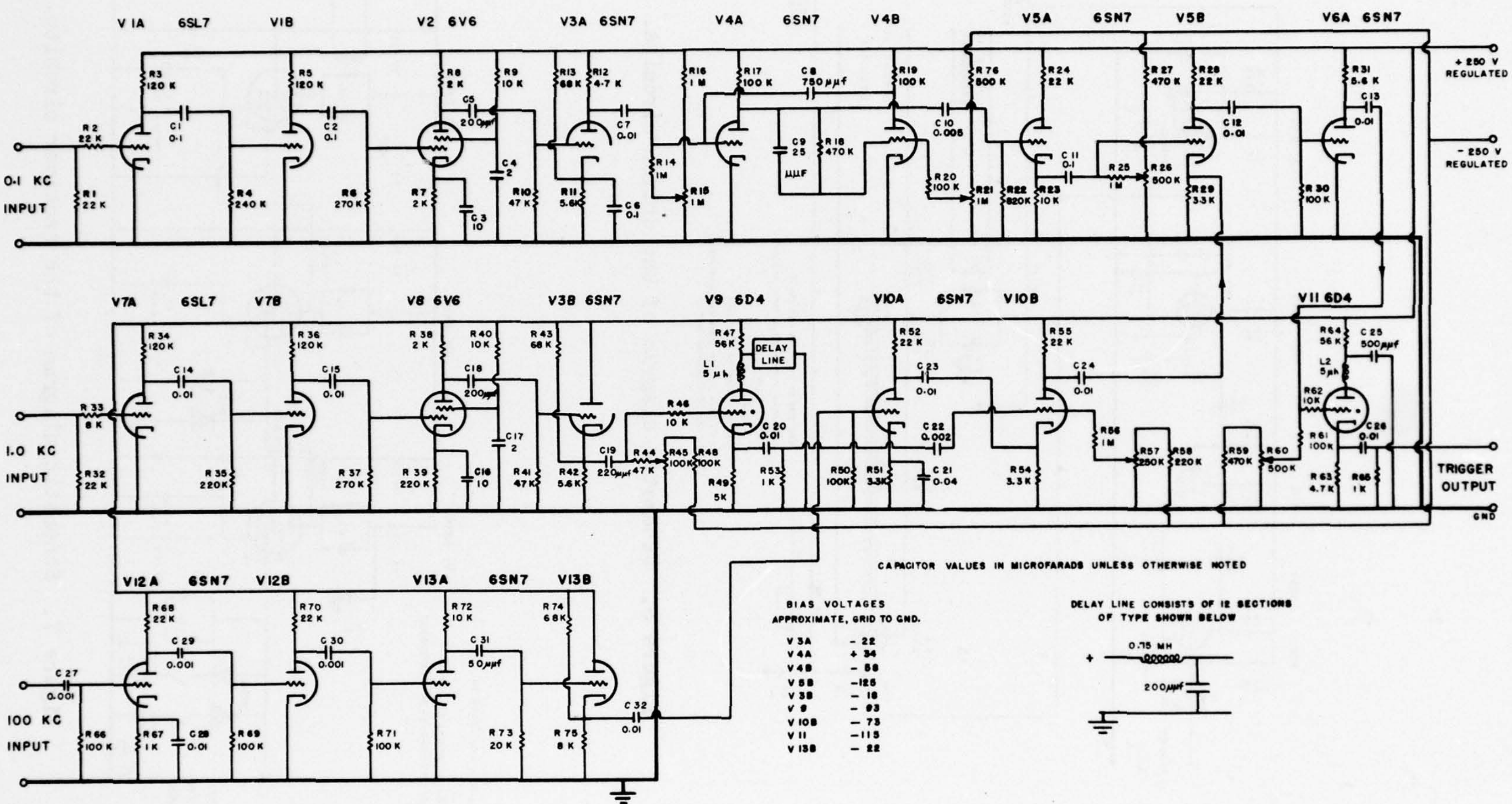

Figure 5. Schematic diagram of the timing circuits.

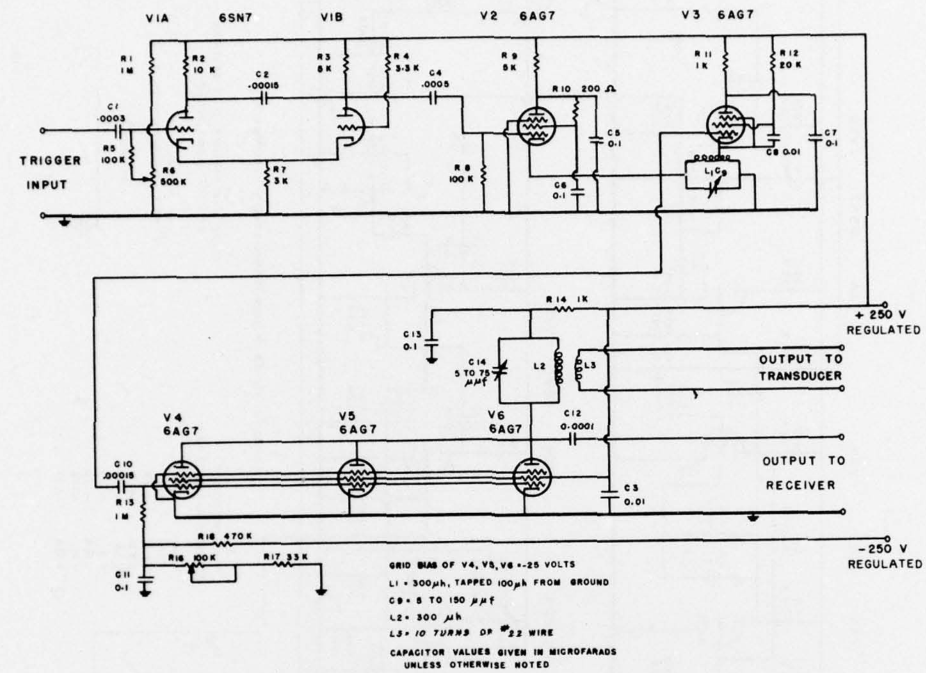

Figure 6. Schematic diagram of the driver circuits.

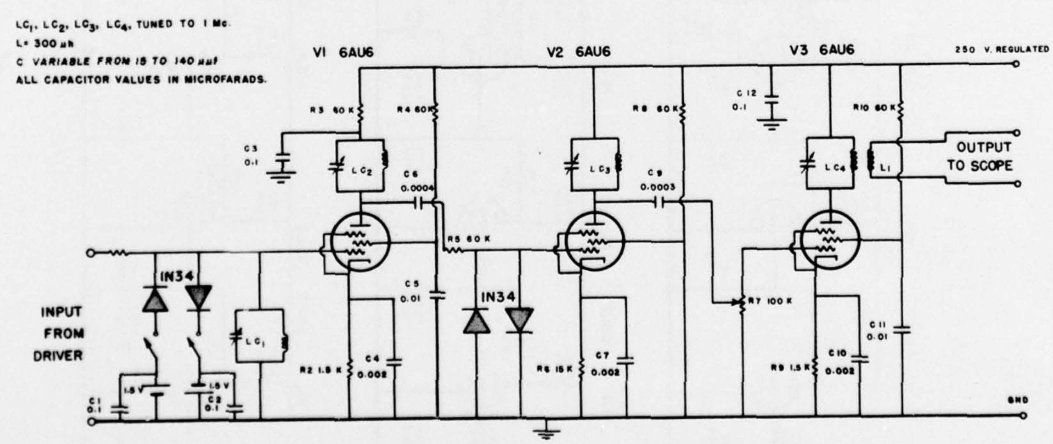

Figure 7. Schematic diagram of the receiver circuits.

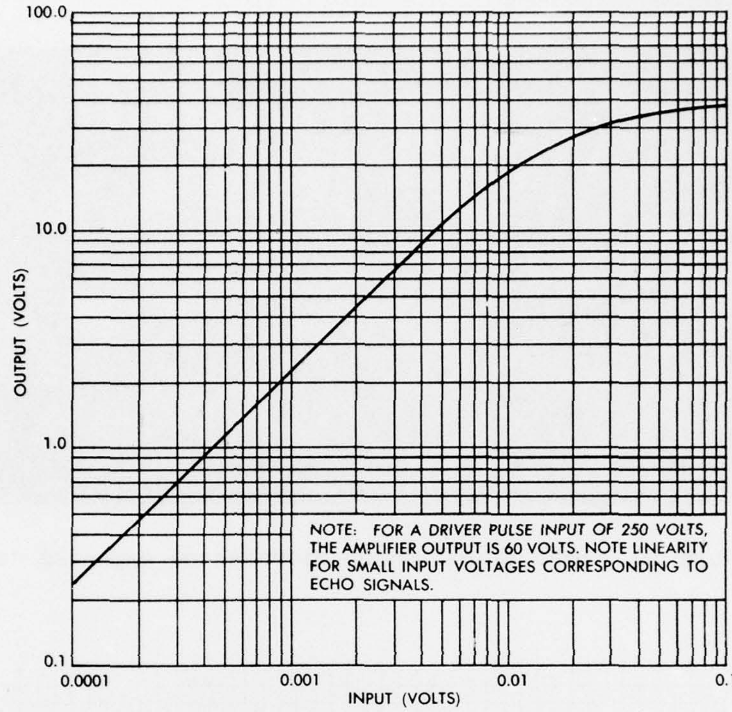

Figure 8. Response curve of the receiving amplifier.

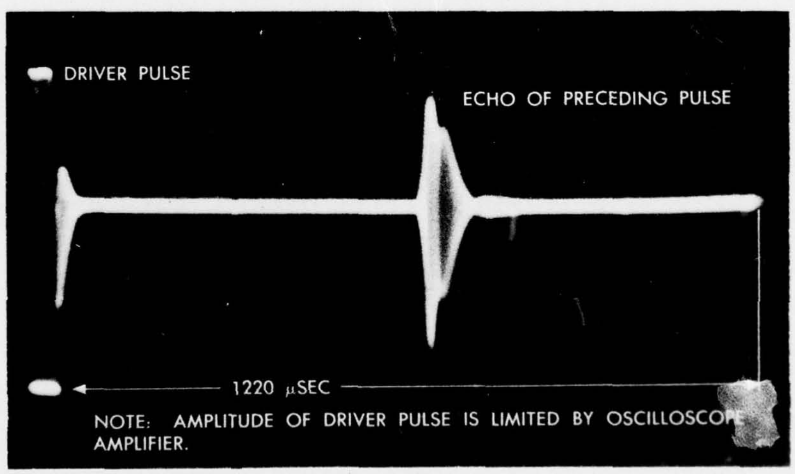

Figure 9. Driver pulse and echo signal on 1220 micro-second sweep.

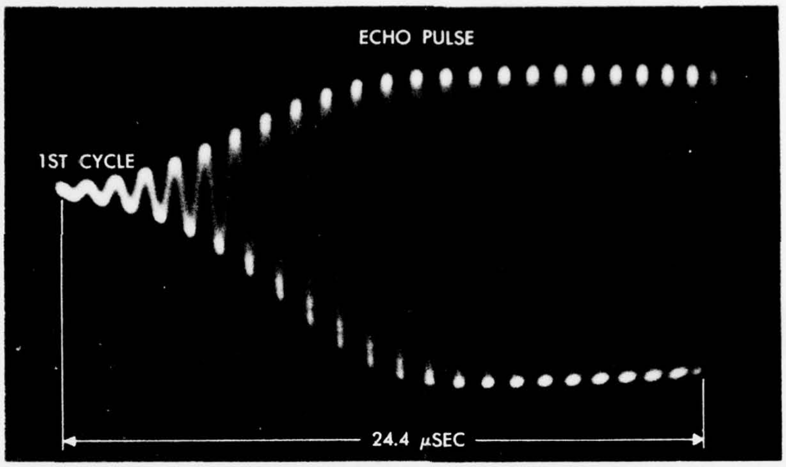

Figure 10. Echo signal on 24 microsecond expanded sweep.

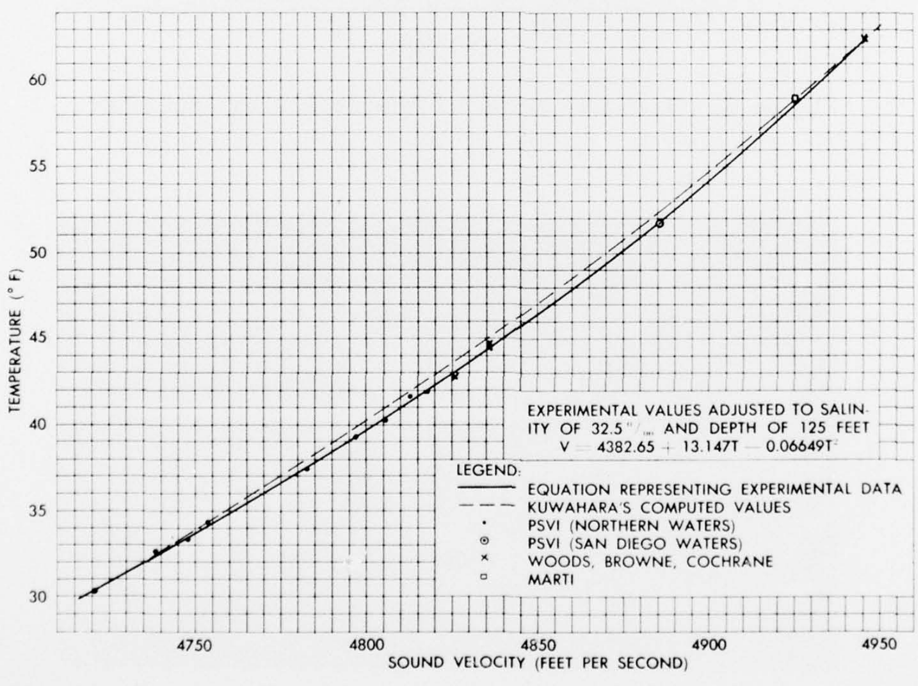

Figure 11. Sound velocity as a function of temperature.

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APPENDIX

100-Kc Preliminary Model X1

To test the feasibility of direct measurements of sound velocity in the sea by an instrument mounted on a submarine, a preliminary model of the PSVI operating at 100 kc was constructed. With the exception of timing circuits most of the components were available in other equipment and needed only minor modifications. Separate transducers were used for the transmitter and receiver. The general installation on the submarine was similar to that of the 1-Mc Model X2.

This equipment was given extensive tests both off San Diego where negative velocity gradients were encountered, and in British Columbia where nearly isothermal water was found. Whenever possible the sound velocity was determined from measurements of temperature, salinity, and depth, and checked against the velocity obtained from the PSVI. Agreement within 5 feet per second was usually obtained, and much of this disparity may be the result of inaccurate temperature measurements. A strong, steady echo was received at all depths up to 200 feet (maximum test depth) regardless of the speed of the submarine. Vertical velocity gradients were measured by reading depth and sound velocity simultaneously at intervals of 10 feet, during slow ascents or descents.

In positioning the echo trace on the oscilloscope (by setting the range dial) an easily identifiable feature of the echo was arbitrarily used as a reference. No difficulty was experienced in recognizing this reference feature even by ship's personnel after only a few minutes' instruction. However, the chief limitation of the equipment was the inability to show that the arbitrary reference selected was the <u>first</u> cycle of the echo. Since the period of 100-kc waves is 10 microseconds, an error of one cycle in the positioning of the echo would cause an error in sound velocity of 5 feet per second. This restricted the use of the instrument to measurement of velocity gradients, or demanded a velocity calibration based upon temperature, salinity, and depth of the water. Use of a higher frequency, 1 Mc, was proposed as a method of reducing the possible error involved in recognizing the initial cycle of the echo, and increasing the accuracy of velocity determinations.

For the measurement of velocity gradients the 100-kc instrument has certain advantages. It is simpler to build, does not require careful alignment of transducers and reflector, and gives a steadier echo, particularly where the velocity structure is rapidly changing. A velocity change of about 0.5 foot per second can be detected with the 100-kc equipment.

